Photometric Observations of Mutual Events in Saturn's System of Regular Satellites in 1995

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Abstract:

We carried out observations of mutual events in Saturn's system of satellites as part of the PHESAT95 International Program. Three light curves of these events were obtained. We developed a technique of allowance for the influence of the law of light reflection from the surfaces of Saturn's satellites, photometric nonuniformity of their surfaces, the phase effect, and the illumination distribution in the satellite penumbra (given the brightness distribution over the solar disk) on the light curve of an occultation or eclipse of one satellite by another. This technique is used to interpret our observations of these events and to determine the minimum separations between satellites or between a satellite and the shadow center of another satellite and the corresponding timings.

Key words: *Solar system —satellites, planets, occullations, eclipses*

Article:

INTRODUCTION

Over the period of Saturn's revolution around the Sun, the Earth crosses the planet's equatorial plane twice. Since Saturn's regular satellites revolve in planes close to its equator, mutual events can be observed: occultations of one satellite by another (O) and eclipses of one satellite by another (E). During observations of these events, the fluxes from the satellites are measured and the time is recorded. The reduction of photometric observations of mutual events involves determining the minimum separation between the satellite centers for occultations or the separations between the center of the eclipsed satellite and the shadow center of the eclipsing satellite, as well as the corresponding time of minimum of the brightness decline. The positional accuracy of determining the relative positions of satellites can reach 0″ 01 (Devyatkin and Bobylev 1995). Observations of mutual events are valuable for developing the theory of satellite motion and for studying the dynamical effects in Saturn's system of satellites.

OBSERVATIONS OF MUTUAL EVENTS

We performed our photometric observations of eclipses of satellites in Saturn's system in August 1995 with the 1-m telescope at the Tien Shan Observatory of the Fesenkov Astrophysical Institute (Ministry of Science, Academy of Sciences of Kazakhstan), located near the Great Almaty Lake (altitude 2800 m), using the FP3U photometer-polarimeter of the Pulkovo Astronomical Observatory (Bergner *et al.* 1988) equipped with a photomultiplier with a GaAs photocathode and a detector thermoelectrically cooled to –20°C. The observations were carried out with a 26" aperture, with the background at an angular distance of 84" subtracted. The brightness of satellites was measured with 15-s exposure times. After each four or five measurements, we visually checked the positions of the objects within the photometer aperture. The measurements were recorded in digital form with an IBM PC AT-286 computer in real time. The accuracy of individual measurements was about 1%.

REDUCTION OF PHOTOMETRIC OBSERVATIONS OF MUTUAL EVENTS

We first reduced our observations by taking into account the following peculiarities of our data: Since all light curves of the events exhibited a temporal trend, we removed the linear trend at all data points, except those at which an event occurred, by least squares and then used the same points to determine the mean flux from the satellites before and after the event. Subsequently, we subtracted the mean flux from all fluxes. Figures 1–3 show the observed total flux from the satellites before, during, and after the events. The flux variations seen in the figures are attributable both to mutual events and to variations in atmospheric transparency. The latter strongly affected the records of the first and third events (Figs. 1, 3). The accuracy of these observations was low, and the signal was at or below the fluctuation level. Nevertheless, we also interpreted these results, although their significance turned out to be very low. The most accurate and reliable results were obtained for event 4O6 (Dione occults Titan).

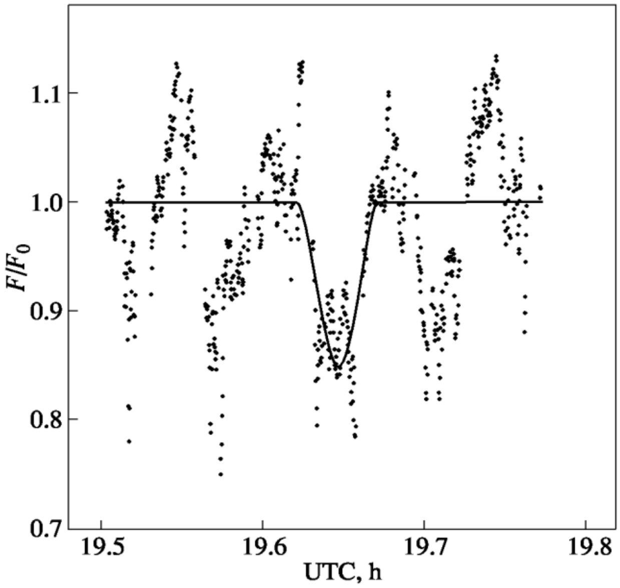


Fig. 1. The light curve of event 2E3 (August 10, 1995; Enceladus eclipses Tethys). The observations are indicated by dots, and the solid line represents the theoretical curve of variations in the total flux from the two satellites.

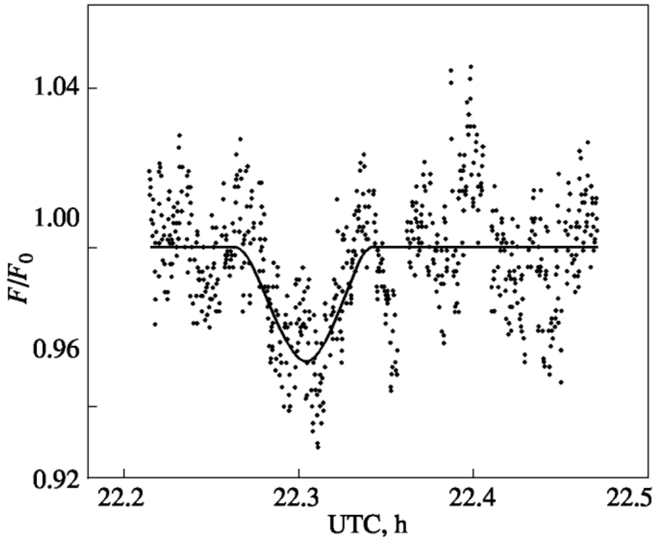


Fig. 2. The light curve of event 4O6 (August 13, 1995; Dione occults Titan). The notation is the same as in Fig. 1.

THE TECHNIQUE OF ALLOWANCE FOR THE PHOTOMETRIC PECULIARITIES OF EVENTS

The satellites for which the data are given in Table 1 belong to the regular group. All of these satellites, except Hyperion, exhibit axial rotation synchronized with their revolution period. Thus, the same side of the satellites always faces Saturn. The photometric data show that some of Saturn's satellites exhibit brightness variations with satellite orbital position (i.e., with orbital phase angle), which is attributable to photometric non-uniformity of the reflecting surface and to synchronous rotation. When the light curves of such events are interpreted, these factors, as well as the law of light reflection from the satellite surface, the phase effect and the illumination distribution in the penumbra must be taken into account. The influence of photometric nonuniformity on positional observations of Jupiter's and Saturn's satellites was considered by Devyatkin and Bobylev (1988, 1991), Devyatkin (1991), and Devyatkin *et al.* (1998). The effects were shown to be significant. Our technique is based on the development of the ideas in the above papers. In our case, we numerically constructed images for each eclipsed or occulted satellite. The following factors were taken into account in the satellite model image:

(1) The law of light reflection from the satellite surface;

(2) Photometric nonuniformity of the reflecting surface;

(3) The phase effect;

(4) The illumination distribution in the penumbra;

(5) The brightness distribution over the solar disk.

The first three factors were taken into account as prescribed in the above papers. The brightness distribution over the disks of Saturn's satellites was computed by using ground-based observations and data from the Voyager spacecraft. The intensity (brightness) distribution over the satellite disk *I*, relative to the satellite total flux *F*, was calculated using the formula (Buratti and Veverka 1984; Bonnie and Buratti 1984)

$$\frac{I}{F} = A\frac{\mu_0}{\mu+\mu_0}f(\alpha)+(1-A)\mu_0,$$

where $f(\alpha) = A + B\alpha + C\alpha^2$ is the phase function of the surface; α is the phase angle; and μ_0 and μ are the cosines of the angles of incidence and reflection, respectively. The parameters used to construct the model, with allowance for photometric nonuniformity of the reflecting surface, are listed in Table 2.

The phase effect, the illumination distribution in the satellite penumbra, and the brightness distribution over the solar disk were taken into account as prescribed by Devyatkin *et al.* (1998). Having computed the brightness distribution over the disk of the occulted or eclipsed satellite, with allowance for all photometric factors, and the illumination distribution in the "umbra + penumbra" region (for eclipses), we simulated the occultation or eclipse (the passage of the disk of one satellite across the disk of another satellite or the passage of the shadow across the satellite disk) and determined the ratio of the flux from the occulted or eclipsed satellite to the total flux from the satellite. These computations were performed in the same way as those for Jupiter's Galilean satellites (Devyatkin *et al.* 1998).

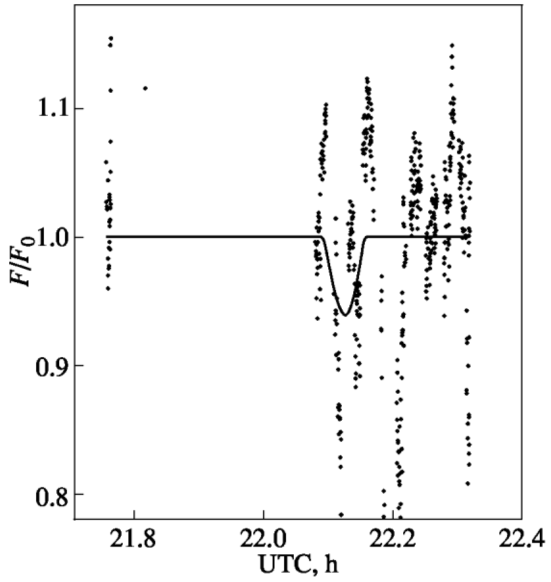


Fig. 3. The light curve of event 2E3 (August 25, 1995; Enceladus eclipses Tethys). The notation is the same as in Fig. 1.

Table 1. Saturn's system of regular satellites (Arlot and Thuillot 1993) (*P* is the revolution period, *R* is the radius, *i* is the orbital inclination, and *V* is the visual magnitude at average opposition)

Satellite	*P*, day	*R*, km	*i*	*V*
Mimas	0.942	196	$1^\circ.563$	$12^m.9$
Enceladus	1.370	250	0.026	11.7
Tethys	1.888	530	1.098	10.2
Dione	2.737	560	0.014	10.4
Rhea	4.518	765	0.347	9.7
Titan	15.945	2575	0.296	8.3
Hyperion	21.277	150	0.644	14.2
Iapetus	79.331	730	14.72	11.1

Table 2. Photometric data for Saturn's satellites (Buratti and Veverka 1984) (*k* is the ratio of the surface albedo of one hemisphere to the surface albedo of the other hemisphere, and θ is the orbital phase angle at which the hemisphere with a larger albedo faces the observer)

Satellite	*A*	*B*	*C*	*f*(0)	*k*	θ, deg
Mimas	0.7	−0.86	0.19	1.1	1.0	–
Enceladus	0.4	−0.51	−0.17	2.4	1.2	270
Tethys	0.7	−0.95	0.20	1.45	1.1	90
Dione	1.0	−1.24	0.50	1.0	1.8	90
Rhea	0.95	1.33	0.54	1.1	1.2	90
Titan	–	–	–	–	1.0	–
Hyperion	–	–	–	–	1.0	–
Iapetus	–	–	–	–	6.9	90

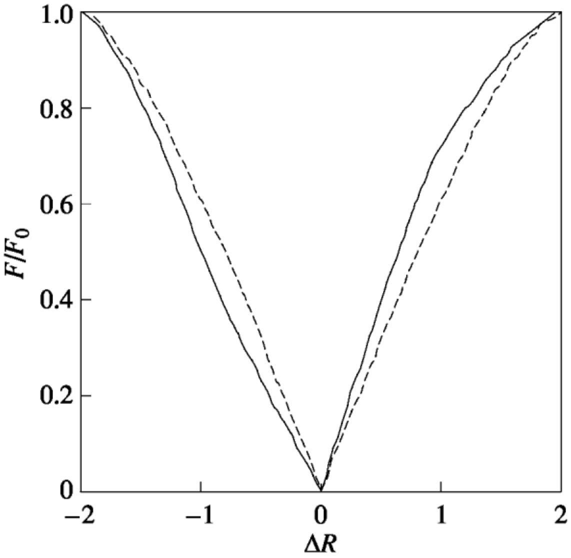


Fig. 4. The effect of photometric nonuniformity of Dione's reflecting surface on the occultation light curve without (dashed line) and with (solid line) allowance for photometric nonuniformity.

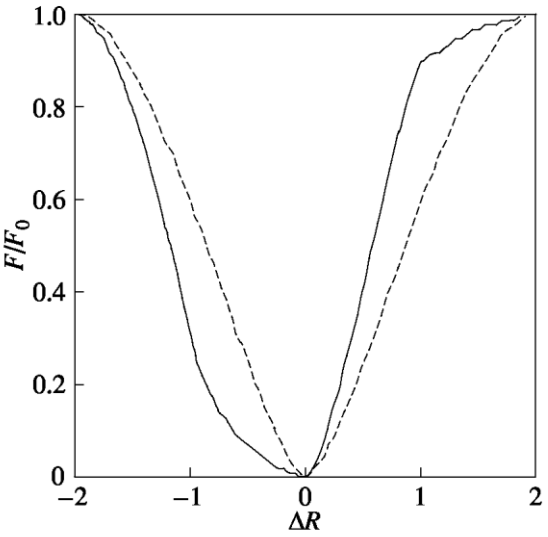


Fig. 5. Same as Fig. 4 for Iapetus.

Figures 4 and 5 present the model curves for the central occultations of Dione and Iapetus by model satellites with the same radius as that of the occulted satellite. In our model, which takes into account photometric nonuniformity of the reflecting surface, we assumed the albedo of one hemisphere of the satellite to be a factor of k larger than that of the other hemisphere (see Table 2). Figures 4 and 5 show an occultation when both the brighter and darker hemispheres of the satellite (with equal areas) are observed. Clearly, when interpreting the observations, an error up to 0.2 and 0.4 in the separation between the satellite centers of the radius for occultations of Dione and Iapetus, respectively, is possible.

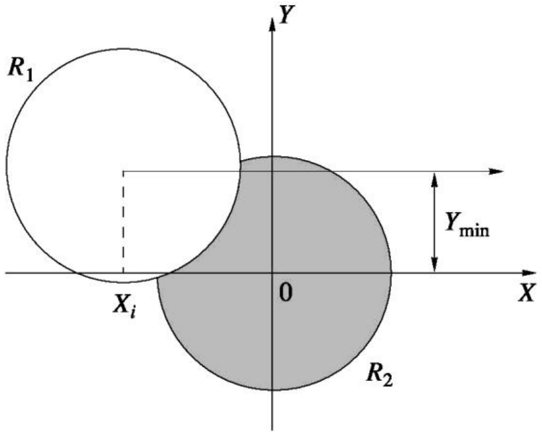


Fig. 6. Geometric elements of the model event in Saturn's system of satellites.

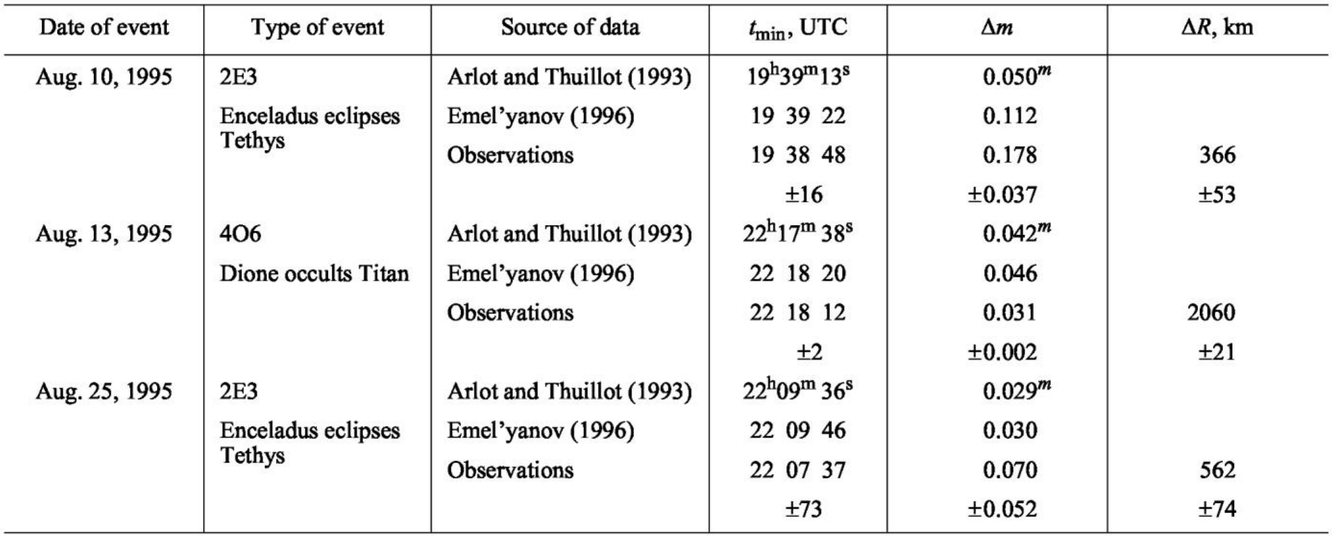
INTERPRETING THE PHOTOMETRIC OBSERVATIONS

Using the technique developed by Devyatkin *et al.* (1998), we computed model occultation and eclipse light curves for various minimum separations between the components of the events [satellite minus satellite, satellite minus (umbra + penumbra)] (see Fig. 6, where R_1 is the occulting satellite or the satellite shadow and R_2 is the occulted or eclipsed satellite). From these light curves, we deduced the flux ratio $E_i(Y_j^{min})/E_0$, where X_i is the separation between the satellite centers (or the separation between the satellite and shadow centers), E_0 is the total flux from the satellites before or after the event, and E_i is the total flux from the satellites during the event at the separation X_i between the components of the event. Subsequently, we fitted the model curves to the observed curve and determined the sums of the squares of the deviations of the observed values from the model values; as a result, we chose the model curve with a minimum of the sum. The position of the minimum of the model curve (relative to the observed curve) was used to determine the time of the observed brightness minimum for the occulted or eclipsed satellite. The minimum separation corresponding to the minimum of the light curve was a parameter for computing the model curve.

Figures 1–3 show the observed light curves for Saturn’s satellites and the computed model curves for these events. The model curves were chosen by using the criterion of a minimum of the squares of the residuals. In all cases, the satellites were observed as a whole, and we did not determine their individual brightnesses. To determine the brightness decline in the occulted satellites relative to the brightness of the unocculted satellite, we used the ephemeris values of the satellite magnitudes.

Table 3 gives the results of our observations, their comparison with the ephemeris values, and other relevant data. As we see from the Table 3, the results for event 2E3 (Enceladus eclipses Tethys) have a low accuracy and are most likely a demonstration of the difficulties of such observations with photometers. It is preferable to observe such events with panoramic detectors, for example, with CCD arrays. In that case, both the background and the satellite brightness can be recorded, and transparency variations can be checked using other objects within the frame.

Table 3. Comparison of the ephemeris (Arlot and Thuillot 1993; Emel’yanov 1996) with our observations ($t_{\min}$ is the time of minimum brightness, Δm is the maximum total decline in brightness of the two satellites, and ΔR is the minimum separation between the satellite centers for occultations or between the satellite and shadow centers for eclipses)



Date of event	Type of event	Source of data	$t_{\min}$, UTC	Δm	ΔR, km
Aug. 10, 1995	2E3	Arlot and Thuillot (1993)	$19^{h}39^{m}13^{s}$	0.050^{m}	
	Enceladus eclipses Tethys	Emel’yanov (1996)	19 39 22	0.112	
		Observations	19 38 48	0.178	366
			±16	±0.037	±53
Aug. 13, 1995	4O6	Arlot and Thuillot (1993)	$22^{h}17^{m}38^{s}$	0.042^{m}	
	Dione occults Titan	Emel’yanov (1996)	22 18 20	0.046	
		Observations	22 18 12	0.031	2060
			±2	±0.002	±21
Aug. 25, 1995	2E3	Arlot and Thuillot (1993)	$22^{h}09^{m}36^{s}$	0.029^{m}	
	Enceladus eclipses Tethys	Emel’yanov (1996)	22 09 46	0.030	
		Observations	22 07 37	0.070	562
			±73	±0.052	±74

CONCLUSION

We have carried out photometric observations of mutual events in Saturn’s system of regular satellites with the 1-m telescope at the Tien Shan Observatory of the Fesenkov Astrophysical Institute (Ministry of Science, Academy of Sciences of Kazakhstan). Two eclipse light curves and one occultation curve were obtained. We interpreted the observations by using a specially developed technique of allowance for the influence of the law of light reflection from the surfaces of Saturn’s satellites, photometric nonuniformity of their surfaces, and the phase effect on the light curves of occultations or eclipses of one satellite by another. We determined the minimum separations between the satellites or between one satellite and the shadow center of another satellite, and the timings of the events. The interpretation of the occultation of Titan by Dione on August 13, 1995, proved to be most reliable.

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